Mapping the Spatial Dynamics in Optically Significant Bottom Nepheloid Layers Using Autonomous Underwater Gliders

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LONG TERM GOALS

Several automated, compact sampling platforms have recently been developed or are gaining widespread use in Naval operations and oceanographic research for mapping environmental parameters in multiple dimensions. In addition to limited sensor payloads, many of these platforms are intended for extended deployments. Sensors compatible with these platforms must therefore be compact, low power, and able to accommodate effective anti-biofouling measures. Developing optical sensors with these qualities for use in Naval operations and oceanographic research is a core long term goal. A related long term goal is developing and implementing inversion algorithms that use optical measurements from gliders and other deployment platforms to derive biogeochemical properties of seawater constituents.

OBJECTIVE

Our objective is to develop a coherent understanding of the dynamics and optics of bottom nepheloid layers. To accomplish this, particle composition characteristics are being resolved with the relevant physical forcing mechanisms across a wide range of time and space scales with Slocum gliders outfitted with newly developed attenuation and backscattering sensors. For the first time, as a result of recent efforts by co-I's Oscar Schofield and Scott Glenn and the PI, we now have the deployment platform and optical sensing technology to adequately address this critical problem.

APPROACH

We used a pair of gliders outfitted with Scattering-Attenuation Meters (SAMs) and backscattering sensors to spatially map the presence of nepheloid layers at the Martha's Vineyard Coastal Observatory (MVCO) during a coordinated experiment with ONR investigators involved in the OASIS program. Measurements complement a series of fixed platform observations currently being made at MVCO. Spatial maps of attenuation and backscattering are being inverted to derive particle composition parameters within nepheloid layers. Inversion algorithms include the Twardowski et al. (2001) algorithm to derive bulk particle refractive index from the backscattering ratio and Twardowski and Zaneveld (2004) approximations to derive mineral and organic particulate material fractions. Analyses of glider optical data from other deployments around the globe are also being carried out to better understand the properties of bottom nepheloid layers.

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For the MVCO deployment, gliders are being used to help discriminate between local and advective processes. Two gliders are being flown along paths normal to the coastline and the mean direction of local currents. In-situ vertical profiler data from ships is also being collected coincidently with the glider data for vicarious calibration and validation.

WORK COMPLETED

- Gliders with optical sensors were flown during the Fall 2005 MVCO deployment into FY06, a time period that included a proximal pass by Tropical Storm Ophelia. Optical data from the gliders were processed, derived parameters to describe particle composition as detailed above were computed, and the data were distributed to PIs collaborating on the project. Vertical profile data were also collected with conventional IOP and hydrographic instrumentation in the vicinity of the glider deployments. Vertical profile data were processed, derived parameters to describe particle composition as detailed above were computed, and the data were distributed to PIs collaborating on the project.

- After the MVCO deployments, SAM sensors that were deployed were calibrated in the lab. Results from subsequent deployments in very clear waters off Hawaii led to an updating of the processing protocol for the SAM data.

RESULTS

Vicarious calibration of attenuation and backscattering with coincident vertical profile data was successfully carried out, with calibrations providing matched data across the entire dynamic range sampled (about 1 order of magnitude) (**Fig. 1**). For the backscattering measurement, the calibration was S1*0.00002-0.003, where S1 is the raw signal in digital counts. For the attenuation measurement, the calibration was ln(S1/S2)*0.88-0.28, where S1 and S2 are both the raw signals from the SAM (short and long pathlength, respectively).

The attenuation calibration was applied to the entire RU05 28 d deployment (**Fig. 2**). A bottom nepheloid layer with increased attenuation relative to the overlying water column is present throughout the sampling period. Occasional episodes of increasing and near uniform attenuation throughout the full water column are observed that in some cases appear associated with strong surface winds and water column mixing. These episodes could be associated with localized resuspension or resuspension occurring in water elsewhere that was then advected into the study area. After Sept. 29, either the sensor became fouled or there was very strong attenuation sustained throughout the water column, outside of the measurable range.

The backscattering calibration was applied to the entire RU05 28 d deployment (**Fig. 3**). The same strong signal in the bottom nepheloid was observed throughout the period, with a similar overall pattern to that observed for attenuation. The relative increase in the nepheloid layer was greater than that for attenuation, however, as evidenced in the ratio of backscattering to attenuation (**Fig. 4**). This ratio is sensitive to changes in particle composition, where increases in the ratio tend to be correlated with increases in particle density (i.e., a larger proportion of suspended mineral particles; see Twardowski et al. 2001). Higher ratios are observed in the bottom nepheloid layer, indicative of a higher relative mineral contribution and a local source, i.e., bottom suspension. Typical ratios of ~0.005 to 0.015 in the overlying water column are typical for coastal waters with particle populations composed of a mixture of “soft” organic particles such as organisms and detrital material and “hard” mineral particles (Twardowski et al. 2001; Boss et al. 2004; Sullivan et al. 2005). When ratios approach 0.005 and below, the population is essentially dominated by living and dead organic particles with substantial interstitial water content. In the bottom nepheloid layer, ratios reach 0.04 in some cases. This is indicative of minerals completely dominating the particle population.

Glider diver visibility was computed from attenuation using the Zaneveld and Pegau (2001) algorithm: 4.8/(cpg650*1.18+0.081). Visibility was always lowest, from ~1 to 6 m, in the ubiquitous bottom boundary layer. During the full water column mixing events, the entire water volume experienced this limited visibility. During periods of stratification, however, the water column overlying the bottom boundary layer exhibited excellent visibilities, from 20 to greater than 30 m.

With both SAM polarized scattering measurements and ECO-BB unpolarized measurements on the glider, the depolarization ratio could be investigated. Theory predicts that the depolarization ratio should be linked to the particle size distribution, where as the ratio increases, approaching its maximum value of 1, small particles should become more important. Preliminary data and analysis showed some promise, but the dependence on the depolarization ratio seemed very weak. Additionally, results from the analysis could not reliably be validated with our current data sets. This is a topic of interest for subsequent deployments.

IMPACT/APPLICATIONS

Progress and results represent important steps toward understanding the optics and dynamics of bottom turbidity layers for Naval operations and oceanographic research. Measurements of Inherent Optical Properties, including attenuation and backscattering, on glider AUVs within bottom nepheloid layers have impacts on several Naval applications, including diver visibility and vulnerability, harbor and port defense and security, debris field mapping, and predicting the performance of active and passive optical MCM identification systems. These measurements are also widely used in research applications for determining particle concentration, particle composition, and water clarity.

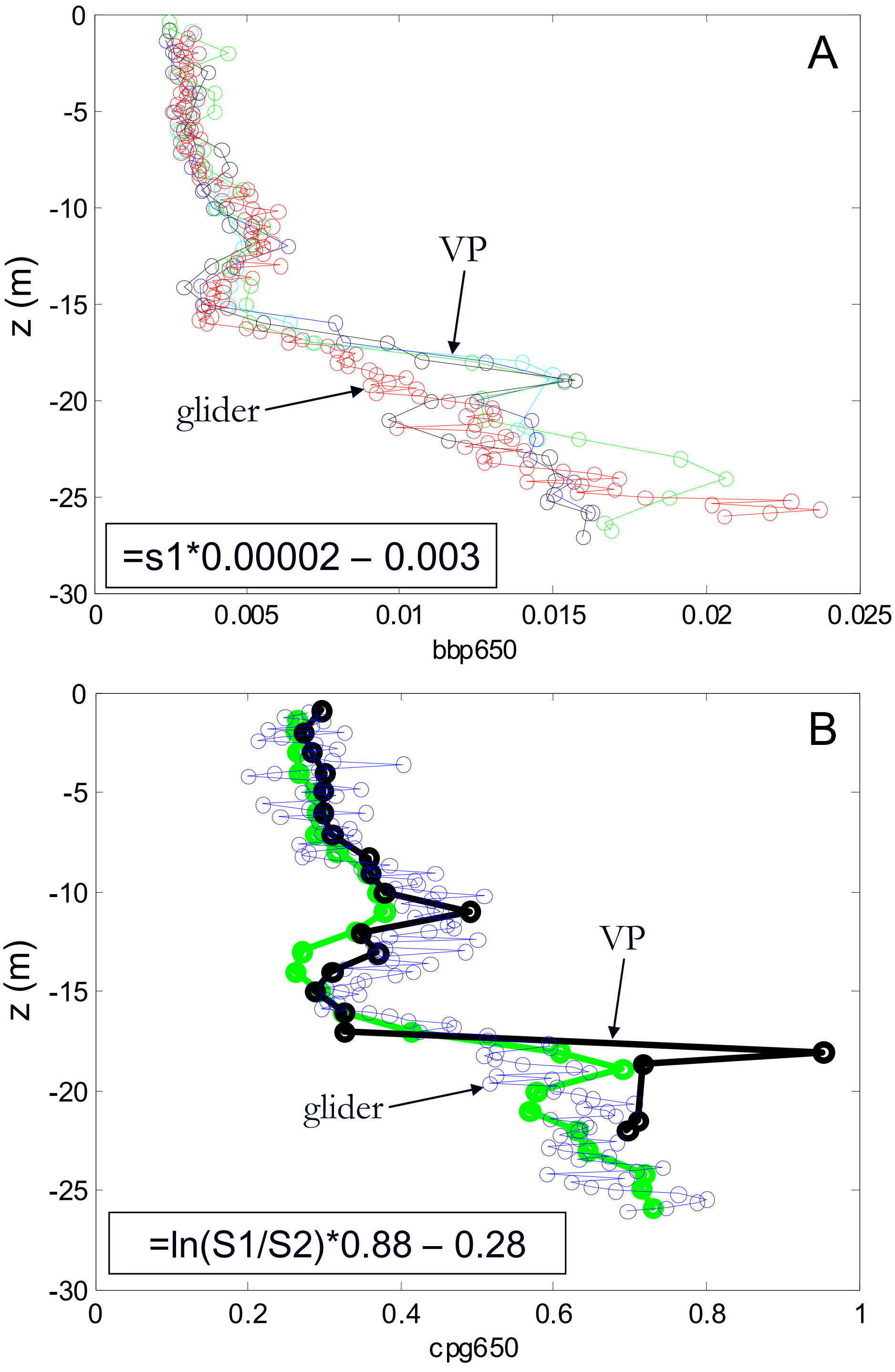

Figure 1. Vicarious calibration of backscattering (A) and attenuation (B) data records from the glider using coincident data from ship-based vertical profiler (VP). The algorithms to process raw signals from the sensors (e.g., S1, S2) are shown in the respective plots.

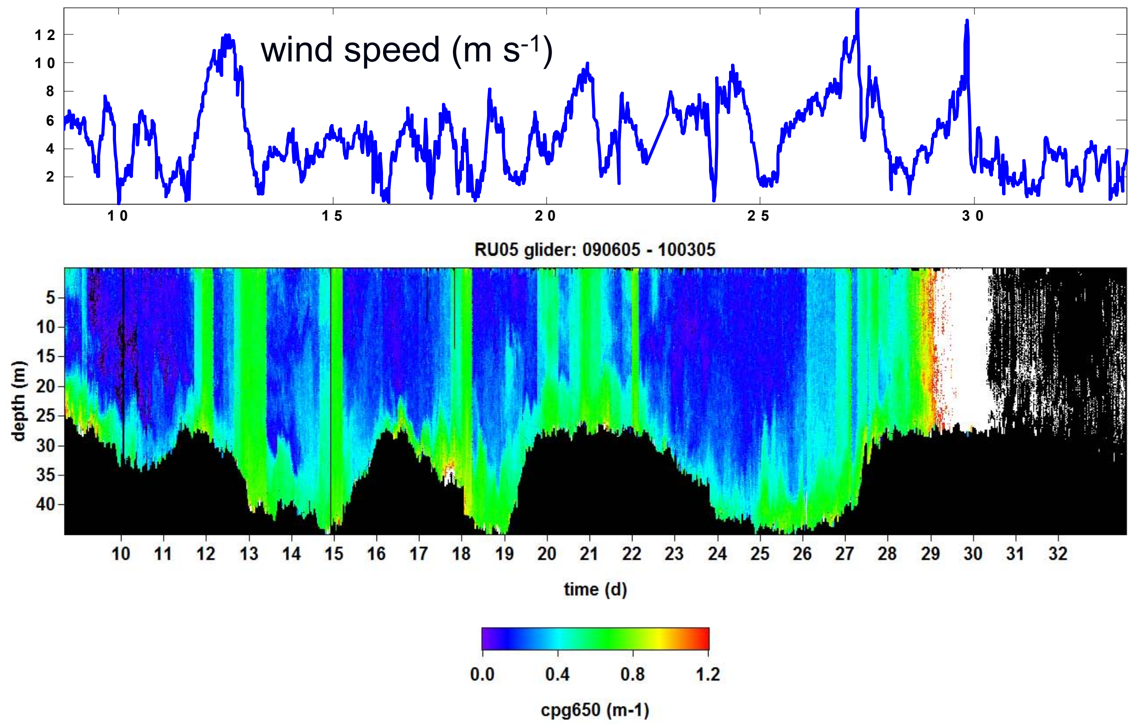

Figure 2. Attenuation measured with the SAM sensor on glider RU05 during the 28 d sampling period. Time is with respect to September day. Wind speed is plotted above the attenuation data. A bottom nepheloid layer with increased attenuation relative to the overlying water column is present throughout the sampling period. Occasional episodes of increasing and near uniform attenuation throughout the full water column are observed that in some cases appear associated with strong surface winds. After Sept. 29, either the sensor became fouled or there was very strong attenuation sustained throughout the water column, outside of the measurable range

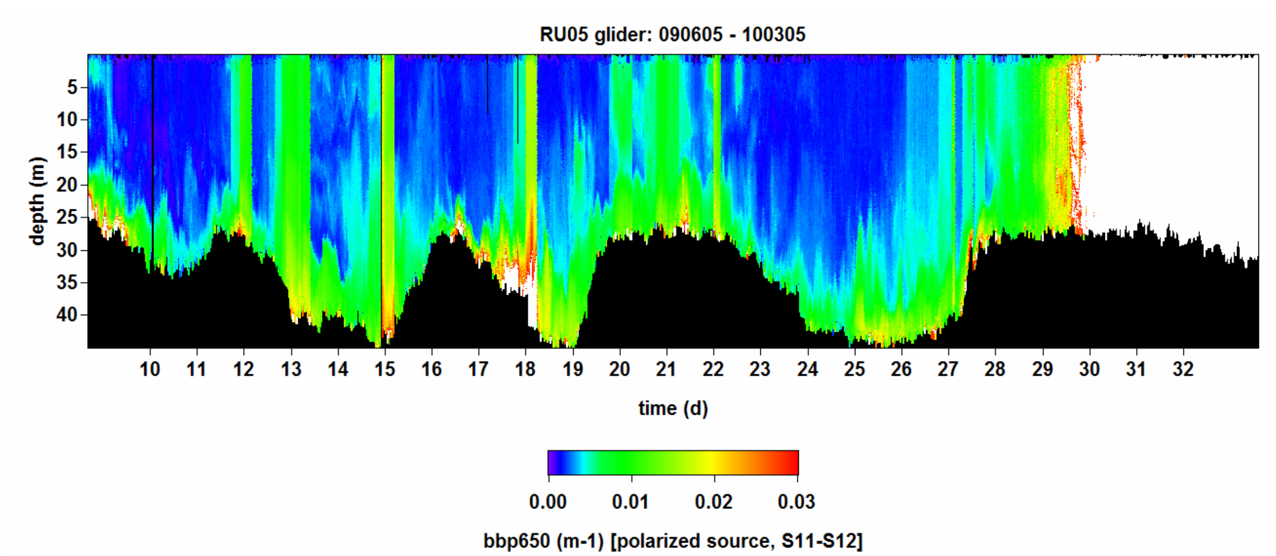

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Figure 3. Backscattering measured with the SAM sensor on glider RU05 during the 28 d sampling period. Patterns are similar to those for attenuation.

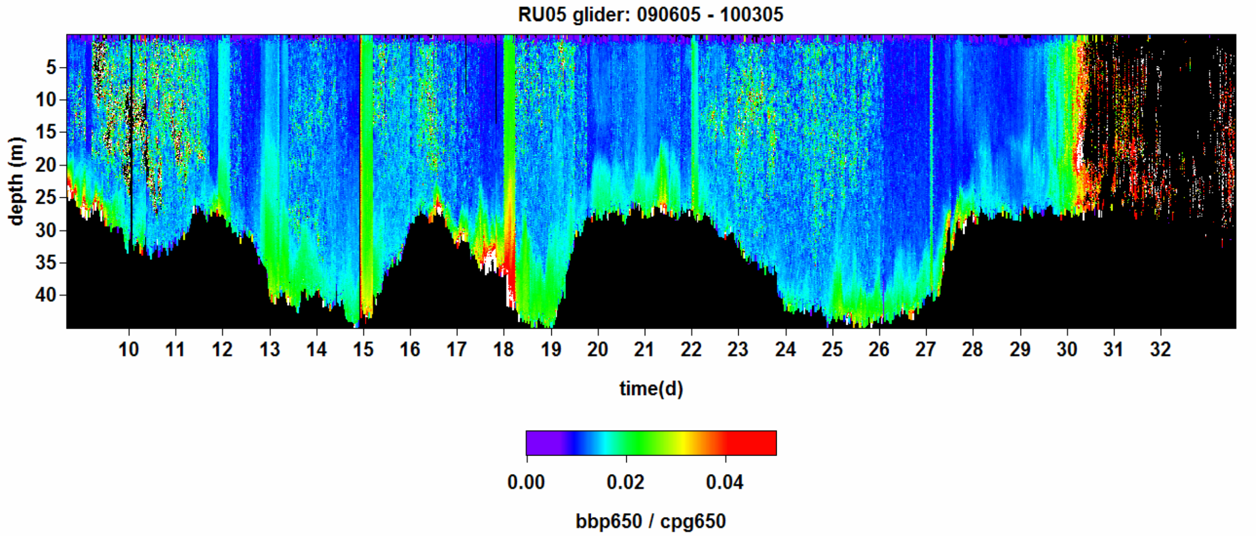

Figure 4. Backscattering to attenuation ratio for the 28 d sampling period. This ratio is sensitive to changes in particle composition, where increases in the ratio tend to be correlated with increases in particle density (i.e., a larger proportion of suspended mineral particles; see Twardowski et al. 2001). Higher ratios are observed in the bottom nepheloid layer, indicative of a higher relative mineral contribution and a local source, i.e., bottom suspension.

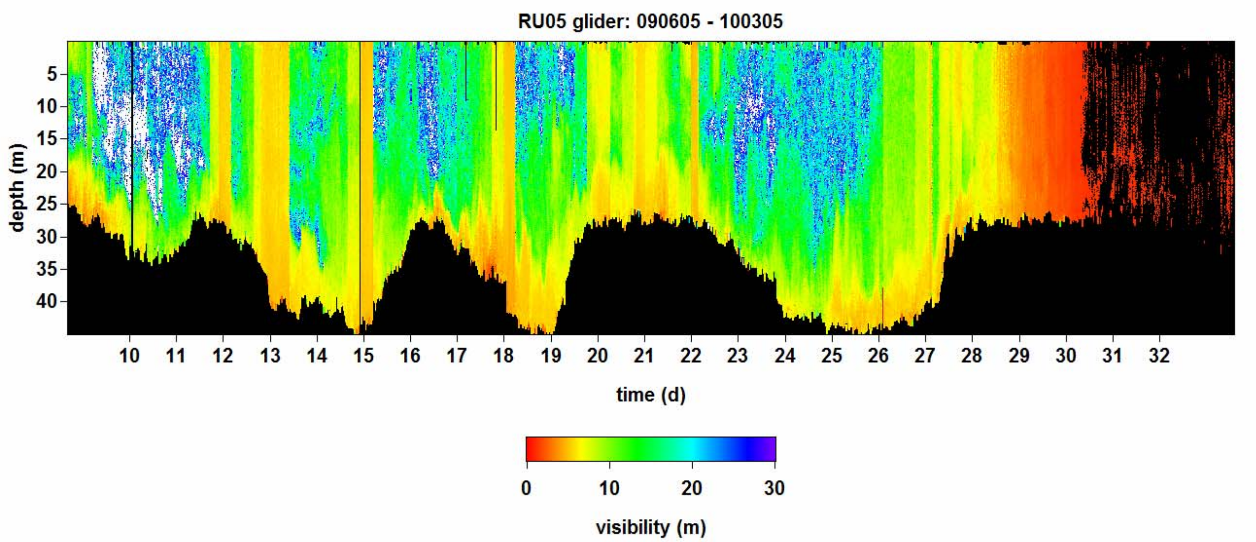

*Figure 5. Diver visibility (horizontal) computed from SAM attenuation measurements according to the algorithm of Zaneveld and Pegau (2001): visibility=4.8/(cpg650*1.18 +0.081). Visibility was always lowest, from ~1 to 6 m, in the ubiquitous bottom boundary layer. During the full water column mixing events, the entire water volume experienced this limited visibility. During periods of stratification, however, the water column overlying the bottom boundary layer exhibited excellent visibilities, from 20 to greater than 30 m.*

TRANSITIONS

We expect that our efforts in developing optical sensors for AUVs and associated biogeochemical inversion techniques will lead to transition of these optical sensors into operational tools for the fleet and the oceanographic research community in the future. The Naval Oceanographic Office is currently interested in applying this technology to map environmental properties in nepheloid layers and beyond.

RELATED PROJECTS

This effort is an extension of ongoing efforts to develop compact optical sensors for AUVs and associated biogeochemical inversion techniques. Related projects include:

- developing a compact total scattering meter for AUVs,

- developing a VSF measurement device called the Multiple Angle SCattering and Optical Transmission (MASCOT) sensor,

- developing novel harbor security monitoring capabilities with Chuck Trees and Jim Mueller,

- developing improved vicarious calibration and validation methods for ocean color satellite remote sensing,

- investigating the sources of backscattering in natural waters with Ron Zaneveld, Heidi Dierssen, and Jim Sullivan, and

- developing tools for ocean observing systems in collaboration with Andrew Barnard, Percy Donaghay, and Jim Sullivan.

PUBLICATIONS IN LAST FIVE YEARS

Boss, E., and M.S. **Twardowski**. 2000. On the relationship of the particulate beam attenuation spectrum and size distribution of oceanic particles. *Proceedings from Ocean Optics XV*, October 16-20, Monaco.

Coleman, J.E., R.A. Reynolds, M.C. Talbot, M.S. **Twardowski**, M.J. Perry. 2000. Utilization of solar-induced chlorophyll a fluorescence as an indicator of phytoplankton biomass in coastal waters. *Proceedings from Ocean Optics XV*, October 16-20, Monaco.

Eisner, L., M.S. **Twardowski**, and T.J. Cowles. 2000. In situ spectral absorption (ac-9) measurements as an index of photoprotective/photosynthetic carotenoid ratios. *Proceedings from Ocean Optics XV*, October 16-20, Monaco.

Moore, C., M.S. **Twardowski**, and J.R.V. Zaneveld. 2000. The ECO VSF - A multi-angle scattering sensor for determination of the volume scattering function in the backward direction. *Proceedings from Ocean Optics XV*, October 16-20, Monaco.

Twardowski, M.S., E. Boss, J.B. Macdonald, W.S. Pegau, A.H. Barnard, and J.R.V. Zaneveld. 2000. A model for retrieving oceanic particle composition and size distribution from measurements of the backscattering ratio and spectral attenuation. *Proceedings from Ocean Optics XV*, October 16-20, Monaco.

Twardowski, M.S. 2000. Ocean research in the ocean state. *The Rhode Island State Trooper,* 12(1):107-109.

Boss, E., W.S. Pegau, W.D. Gardner, J.R.V. Zaneveld, A.H. Barnard, M.S. **Twardowski**, G.C. Chang, and T.D. Dickey. 2001. Spectral particulate attenuation in the bottom boundary layer of a continental shelf. *J. Geophys. Res.*, 106(C5):9509-9516. [refereed]

Boss, E., M.S. **Twardowski**, and S. Herring. 2001. Shape of the particulate beam attenuation spectrum and its inversion to obtain the shape of the particulate size distribution. *Appl. Opt.,* 40:4885-4893. [refereed]

Dekshenieks, M.M., P.L. Donaghay, J.M. Sullivan, J.E.B. Rines, T.R. Osborn, and M.S. **Twardowski**. 2001. Temporal and spatial occurrence of thin phytoplankton layers in relation to physical processes. *Mar. Ecol. Prog. Ser.,* **223**:61-71. [refereed]

Twardowski, M.S. and A. Barnard. 2001. Observing the ocean: sensing technology and observation platforms. *Maritimes*, 43(4).

Twardowski, M.S., and P.L. Donaghay. 2001. Separating in situ and terrigenous sources of absorption by dissolved material in coastal waters. *J. Geophys. Res.*, 106(C2):2545-2560. [refereed]

Twardowski, M.S., E. Boss, J.B. Macdonald, W.S. Pegau, A.H. Barnard, and J.R.V. Zaneveld. 2001. A model for estimating bulk refractive index from the optical backscattering ratio and the implications for understanding particle composition in Case I and Case II waters. *J. Geophys. Res.,* 106(C7):14,129-14,142. [refereed]

Gould, R., R. Stavn, M. **Twardowski**, and G. Lamella. 2002. Partitioning optical properties into organic and inorganic components from ocean color imagery. *Proceedings from Ocean Optics XVI*, November 18-22, Santa Fe, NM.

Rines, J.E.B., P.L. Donaghay, M. Dekshenieks, J.M. Sullivan, and M.S. **Twardowski**. 2002. Thin layers and camouflage: hidden *Pseudo-nitzschia spp*. (Bacillariophyceae) populations in a fjord in the San Juan Islands, Washington, U.S.A. *Mar. Ecol. Prog. Ser.*, 225:123-137. [refereed]

Sullivan, J.M., M.S. **Twardowski**, P.L. Donaghay, and S. Freeman. 2002. Particulate bulk refractive index distributions in coastal regions as determined from backscattering ratio measurements. *Proceedings from Ocean Optics XVI*, November 18-22, Santa Fe, NM.

Twardowski, M.S., and P.L. Donaghay. 2002. Photobleaching of aquatic dissolved materials: absorption removal, spectral alteration, and their interrelationship. *J. Geophys. Res,* 107(C8). [refereed]

Twardowski, M.S., J.R.V. Zaneveld, and C. Moore. 2002. A novel technique for determining beam attenuation compatible with a small sensor form factor and compact deployment platforms. *Proceedings from Ocean Optics XVI*, November 18-22, Santa Fe, NM.

Zaneveld, J.R.V., M.S**. Twardowski**, K.S. Shifrin, W.S. Pegau, E. Boss, and I. Zolotov. 2002. Inversion of light scattering measurements to obtain biogeochemical parameters. *Proceedings from Ocean Optics XVI*, November 18-22, Santa Fe, NM.

Dekshenieks, M.M., AL Alldredge, A Barnard, E Boss, J Case, TJ Cowles, PL Donaghay, LB Eisner, DJ Gifford, CF Greenlaw, C Herren, DV Holliday, D Johnson, S MacIntyre, D McGehee, TR Osborn, MJ Perry, R Pieper, JEB Rines, DC Smith, JM Sullivan, MK Talbot, MS **Twardowski**, A Weidemann and JR Zaneveld. 2003. Characteristics, Distribution and Persistence of Thin Layers Over a 48 Hour Period. *Mar. Ecol. Prog. Ser.,* 261:1-19. [refereed]

Eisner, L., M.S. **Twardowski**, and T.J. Cowles. 2003. Relationship between phytoplankton pigment composition and in situ spectral absorption measurements in East Sound, Orcas, Island, WA. *Limnol. Oceanogr.,* 48:632-646. [refereed]

Miller, R., M.S. **Twardowski**, C. Moore, and C. Casagrande. 2003. The Dolphin: Technology to Support Remote Sensing Bio-optical Algorithm Development and Applications. *Backscatter* 14(2):8-12.

Boss, E., W. S. Pegau, M. Lee, M. S**. Twardowski**, E. Shybanov, G. Korotaev, and F. Baratange. 2004. The particulate backscattering ratio at LEO 15 and its use to study particles composition and distribution*. J. Geophys. Res.*, 109, C01014, doi:10.1029/2002JC001514. [refereed]

Moore, C., J. Da Cuhna, B. Rhoades, M.S. Twardowski, J.R.V. Zaneveld, J. Dombroski. 2004. A new in-situ measurement and analysis system for excitation-emission fluorescence in natural waters. *Proceedings of Ocean Optics XVII*, October 25-29, Freemantle, Australia.

Schofield, O., J. Kohut, J. Kerfoot, L. Creed, C. Mugdal, S. Glenn, M. **Twardowski**, C. Jones, and D. Webb. 2004. Dawn in the age of ocean robots: what can they see? *Proceedings of Ocean Optics XVII*, October 25-29, Freemantle, Australia.

Sullivan, J.M., M.S. **Twardowski**, J.R.V. Zaneveld, C. Moore, B. Rhoades, and R. Miller. 2004. The hyperspectral temperature and salinity dependent absorption coefficients of pure water. *Proceedings of Ocean Optics XVII*, October 25-29, Freemantle, Australia.

Twardowski, M.S., and J.R.V. Zaneveld. 2004. Progress toward a Generalized Optical-Biogeochemical Inversion (GOBI) for natural waters. *Proceedings of Ocean Optics XVII*, October 25-29, Freemantle, Australia.

Twardowski, M.S., E. Boss, J.M. Sullivan, and P.L. Donaghay. 2004. Modeling spectral absorption by chromophoric dissolved organic matter (CDOM**)**. *Mar. Chem.,* 89: 69-88, doi:10.1016/j.marchem.2004.02.008. [refereed]

Zaneveld, J.R.V., C. Moore, A.H. Barnard, M.S. **Twardowski**, and G.C. Chang. 2004. Correction and analysis of spectral absorption data taken with the WET Labs AC-S. *Proceedings of Ocean Optics XVII*, October 25-29, Freemantle, Australia.

Sullivan, J.M., M.S. **Twardowski**, Donaghay, P.L., and Freeman, S.A. 2005. Using Scattering Characteristics to Discriminate Particle Types in US Coastal Waters, *Appl. Opt*., 44:1667-1680. [refereed]

Trees, C.C., P.W. Bissett, H,. Dierssen, D.D.R. Kohler, M.A. Moline, J.L. Mueller, R.E. Pieper, M.S. **Twardowski**, and J.R.V. Zaneveld. 2005. Monitoring water transparency and diver visibility in ports and harbors using aircraft hyperspectral remote sensing. *Prodeedings from SPIE Port and Harbor Security Conference*, Vol. 5780, February, Orlando, FL.

Twardowski, M.S., M. Lewis, A. Barnard, J.R.V. Zaneveld. 2005. In-water instrumentation and platforms for ocean color remote sensing applications. *In:* Remote Sensing of Coastal Aquatic Waters, R. Miller and C. Del-Castillo [Eds.], Springer-Kluwer Publishing, pp. 69-100. [refereed]

Twardowski, M.S., J.R.V. Zaneveld, C.M. Moore, J. Mueller, C. Trees, O. Schofield, S. Freeman, T. Helble, and G. Hong. 2005. Diver visibility measured with a compact scattering-attenuation meter (SAM) compatible with AUVs and other small deployment platforms. *Prodeedings from SPIE Port and Harbor Security Conference*, Vol. 5780, February, Orlando, FL.

Zaneveld, J.R.V., M.S. **Twardowski**, M. Lewis, and A. Barnard. 2005. Radiative transfer and remote sensing. *In*: Remote Sensing of Coastal Aquatic Waters, R. Miller and C. Del-Castillo [Eds.], Springer-Kluwer Publishing, pp. 1-20. [refereed]

Aurin, D., H. Dierssen, and M. **Twardowski**. 2006. Absorption, Backscatter and Chlorophyll Algorithms for Ocean Color Remote Sensing in Long Island Sound. *Proceedings of Ocean Optics XVIII*, October 9-13, Montreal, Canada.

Sullivan, J.M., M.S. **Twardowski**, J.R.V. Zaneveld, C. Moore, A. Barnard, P. Donaghay, and B. Rhoades. 2006. The hyperspectral temperature and salinity dependencies of absorption by water and heavy water in the 400-750 nm spectral range. *Appl. Opt.*, 45:5294-5309. [refereed]

Twardowski M., and M. Jonasz. 2006. VSF at the small angles for natural dispersions and power-law slopes (www.tpdsci.com/Tpc/VsfSmlAngNatDspSlp.php). In: *Topics in Particles and Dispersion Science* (www.tpdsci.com). [refereed]

Twardowski M., and M. Jonasz. 2006. Power law in spectral scattering by natural dispersions: Derivation (www.tpdsci.com/Tpc/AtnCfSptPwLwNatDsp.php). In: *Topics in Particles and Dispersion Science* (www.tpdsci.com). [refereed]

Twardowski M., and M. Jonasz. 2006. Power law in spectral scattering by natural dispersions: Finite range of the particle diameter (www.tpdsci.com/Tpc/AtnCfSptPwLwNatDsp.php). In: *Topics in Particles and Dispersion Science* (www.tpdsci.com). [refereed]

Zaneveld, J.R.V, M.S. **Twardowski**, and C. Moore. 2006. Total scattering coefficient meter. *Proceedings of Ocean Optics XVIII*, October 9-13, Montreal, Canada.

PATENTS

Scattering attenuation meter (SAM), pending.

HONORS/AWARDS/PRIZES

Twardowski, M., 2005: *Spinoff* technology selection, NASA Innovative Partnership Program, http://www.sti.nasa.gov/tto/Spinoff2005/PDF/accessible.pdf, p. 62.

Twardowski, M., 2003: Adjunct Professor, University of Rhode Island.

Twardowski, M., 2000: ASEE Visiting Faculty Fellowship, Naval Research Labs.

Twardowski, M., 2000: Early Career Faculty Award, Office of International Research and Development, Oregon State University.

Twardowski, M., 1998: WET Labs Environmental Optics Postdoctoral Fellowship, Oregon State University.